IMPROVED SPACECRAFT MATERIALS FOR RADIATION PROTECTION
Shield materials optimization and testing

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Introduction

Methods by which radiation shielding is optimized need to be developed and materials of improved shielding characteristics identified and validated. The GCR are very penetrating and the energy absorbed by the astronaut behind the shield is nearly independent of shield composition and even the shield thickness. However, the mix of particles in the transmitted beam changes rapidly with shield material composition and thickness. This results in part from the breakup of the high-energy heavy ions of the GCR which make contributions to biological effects out of proportion to their deposited energy. So the mixture of particles in the radiation field changes with shielding and the control of risk contributions from dominant particle types is critical to reducing the hazard to the astronaut. The risk of biological injury for a given particle type depends on the type of biological effect and is specific to cell or tissue type [1,2,3]. Thus, one is faced with choosing materials which may protect a given tissue against a given effect but leave unchanged or even increase the risk of other effects in the same tissue or increase the risks to other adjacent tissues of a different type in the same individual. The optimization of shield composition will then be tied to a specific tissue and risk to that tissue. Such peculiarities arise from the complicated mixture of particles, the nature of their biological response, and the details of their interaction with material constituents.

Aside from the understanding of the biological response to specific components, one also needs an accurate understanding of the radiation emerging from the shield material. This latter subject has been a principal element of this project. In the past ten years our understanding of space radiation interactions with materials has changed radically, with a large impact on shield design. For example, the NCRP estimated that only 2 g/sq. cm. of aluminum [4] would be required to meet the annual 500 mSv limit for the exposure of the blood forming organs (this limit is strictly for LEO but can be used as a guideline for the Mars mission analysis). The current estimates require aluminum shield thicknesses above 50 g/sq. cm. which is impractical. In such a heavily shielded vehicle, the neutrons produced throughout the vehicle also contribute significantly to the exposure and this demands greater care in describing the angular dependence of secondary particle production processes. As such the continued testing of databases and transport procedures in laboratory and spaceflight experiments has continued. This has been the focus of much of the last year’s activity and has resulted in improved neutron prediction capability [5]. These new methods have also improved our understanding of the surface environment of Mars. The Mars 2003 NRA HEDS related surface science requirements were driven by the need to validate predictions on the upward flux of neutrons produced in the Martian regolith and bedrock made by the codes developed under this project [6]. The codes used in the surface environment definition are also being used to look at *in situ* resources for the development of construction materials for Martian surface facilities. For example, synthesis of polyimides and polyethylene as binders of regolith for developing basic structural elements has been studied and targets built for accelerator beam testing of radiation shielding properties [7]. Preliminary mechanical tests have also been promising.

Improved spacecraft materials have been identified (using the criteria reported by this project at the last conference) as potentially important for future shielding materials. These are liquid hydrogen, hydrogenated nanofibers, liquid methane, LiH, Polyethylene, Polysulfone, and Polyetherimide (in order of decreasing shield performance). Some of the materials are multifunctional and are required for other onboard systems. We are currently preparing software for trade studies with these materials relative to the Mars Reference Mission as required in the project's final year.

Methodologies

The types and energy distributions of particles transmitted through a shield material requires the solution to a transport description of the process with appropriate boundary conditions related to the external space radiation environment. The relevant transport equations are the linear Boltzmann equations derived on the basis of conservation principles [8] for the flux density $\phi_j(\mathbf{x},\Omega,E)$ of type j particles moving in direction Ω with energy E as

$$\Omega \bullet \nabla\phi_j(\mathbf{x},\Omega,E) = \sum\int \sigma_{jk}(\Omega,\Omega',E,E')\ \phi_k(\mathbf{x},\Omega',E')\ d\Omega'\ dE' - \sigma_j(E)\ \phi_j(\mathbf{x},\Omega,E) \qquad (1)$$

where $\sigma_j(E)$, $\sigma_{jk}(\Omega,\Omega',E,E')$ are the media macroscopic cross sections for various atomic and nuclear processes including spontaneous disintegration. In general, there are hundreds of particle fields $\phi_j(\mathbf{x},\Omega,E)$ with several thousand cross-coupling terms $\sigma_{jk}(\Omega,\Omega',E,E')$ through the integral operator in equation (1). The total cross section $\sigma_j(E)$ with the medium for each particle type of energy E may be expanded as

$$\sigma_j\,(E) = \sigma_{j,at}\,(E) + \sigma_{j,el}\,(E) + \sigma_{j,r}\,(E) \qquad (2)$$

where the first term refers to collision with atomic electrons, the second term is for elastic nuclear scattering, and the third term describes nuclear reactive processes and are ordered as $10^8:10^5:1$. This ordering allows flexibility in expanding solutions to the Boltzmann equation as a sequence of physical perturbative approximations. Special problems arise in the perturbation approach for neutrons for which the nuclear elastic process appears as the first-order perturbation and has been the recent focus of research [5] as follows.

The double differential particle production and fragmentation cross sections $\sigma_{jk}(\Omega,\Omega',E,E')$ of equation (1) are separated into an isotropic contribution and a remainder as

$$\sigma = \sigma_F + \sigma_{iso} \qquad (3)$$

where the remainder σ_F consists of only forward directed secondary particles and σ_{iso} is dominated by lower energy particles produced in the reaction. The low energy charged particles can be solved analytically [8] but the low energy neutrons require a different solution technique [5]. The solution to equation (1) can likewise be separated into two parts for which σ_F appears only in equation (1) with solution ϕ_F and a second equation in which σ_{iso} appears in equation (1) but with source terms from coupling to the ϕ_F field through σ_{iso}. The solution to equation (1) for ϕ_F can be written in operational form as

$$\phi_F = G_F\, \phi_B \qquad (4)$$

where ϕ_B is the inbound flux at the boundary, and G_F is the Green's function associated with σ_F which reduces to a unit operator on the boundary. There remains the evaluation of the remainder terms σ_{iso} of equation (1), especially the low-energy neutron transport. The remainder of equation (1) following the separation given by equation (3) is

$$\Omega \bullet \nabla\phi_j(\mathbf{x},\Omega,E) = \sum\int \sigma_{iso,jk}(E,E')\ \phi_k(\mathbf{x},\Omega',E')\ d\Omega'\ dE' - \sigma_j(E)\ \phi_j(\mathbf{x},\Omega,E) + g_j(E,\mathbf{x}) \qquad (5)$$

where the source term $g_j(E,\mathbf{x})$ results from the collisional σ_{iso} source with the ϕ_F field. The charged particle fields of equation (8) can be solved analytically [8] leaving the low-energy neutrons fields to be evaluated using energy multigroup methods [5,9]. It requires a solution to a boundary value problem for the distribution of neutron sources along a 512 array of directions about each location within the vehicle where the fields are to be evaluated. The solution methodology implies a great deal of repeated operations (for each direction) with differences only in the distribution of source terms, distances to the boundaries, and boundary conditions which can be done efficiently with a parallel processor. Other parallel operations could also be used in the solution of the ϕ_F fields solved by marching procedures.

The extent of the nuclear interaction cross section database required for the transport of cosmic rays spans most nuclear-reaction physics from thermal energies to energies above tens of GeV/nucleon, including a large number of projectile and target material combinations. The types of cross sections required for the transport involve total yields and secondary energy spectra for one-dimensional transport and double differential cross sections in angle and energy for three-dimensional transport. The usual approach to database generation is the use of Monte Carlo models or hydrodynamic models with limited usefulness and success. The uniquely LaRC approach has been to develop solution procedures of the basic quantum mechanics using the multiple scattering formalism [10-15].

Validation

Laboratory validation with well defined ion beams and target geometries with high resolution test equipment allows the testing of the atomic/nuclear database and material transmission factors in great detail. One type of database test [16] is shown in Fig. 1 for 1.05 GeV/nucleon iron beams on several targets. The results of the quantum multiple scattering model is shown here in comparison with the experiments. The cross section for removal of a few protons is strongly affected by the single particle model for the nuclear wave functions and the development of a cluster model database is required. Only a small sample of ion and material combinations have so far been tested.

Spaceflight testing allows validation of the full complement of methods (environmental models, materials interaction database, computational procedures, methods of analysis) required to produce exposure field estimates. Most validation is limited to measurements in a predominantly 2219-aluminum alloy structure (Shuttle). Earlier testing was with a particle telescope [17] and more recently with a tissue equivalent proportional counter (TEPC) [18] shown in Fig. 2 with the model calculation [18]. Thediscrepancy in the lowest lineal energies in the GCR spectrum is believed in part due to the neglect of pions in the present shielding model and in part from wall effects in the TEPC not included in the detector response model but important for HZE ions [18]. Neutron measurements [19] using 4 Bonner spheres and activation foils on STS-31 and STS-36 have been very encouraging.

Optimization Methods

A large fraction of the shielding on human rated vehicles is from the basic structure and onboard systems [8]. Engineering design usually proceeds with little regard to radiation constraints until the latter stages of the design process, in part, due to the use of Monte Carlo methods which require great amounts of dedicated computer time resulting in design delays [7]. At such a late stage in the design process, a fix of a radiation problem usually involved adding shielding in less than optimum ways (for example, a 5,500 kg vault was added to Skylab requiring additional support structures). A similar problem now exists with the International Space Station in which redesign is in progress. Clearly, improved methods of design in which radiation constraints are entered early into the design process allowing optimum radiation risk mitigation are required. Since the basic structure and onboard systems provide much of the shielding, the optimization of the spacecraft shielding cannot be done in a vacuum and is inherently a multidisciplinary design process. With the rapid expansion of high performance computing and communication, there is increased emphasis on multidisciplinary optimization (MDO) methods and radiation constraints analysis needs to be added to the collection of tools available to mission design teams. It also requires that materials proposed for other mission design requirements (structure, thermal, noise reduction, expendables…) are multifunctional in character since their radiation shielding properties impact the radiation constraints.

Future Materials Research

Required materials research falls into three categories: First is the improvement of computational models and associated databases. Second is the development of multifunctional material properties for use in system optimization procedures. Third is the design of optimum radiation protective materials to finish out deficiencies in the shield design at minimum mass and costs.

Computational models and databases. The computational models required are the basic atomic and nuclear physics models for database evaluation and the associated transport models which combine these databases to evaluate material transmission properties. Three issues discussed in prior sections relate to needs in the nuclear database and transport procedures. First, the few proton removal cross sections depend on the representation of the outer shells of the nuclear models. Most reaction codes (e.g., Monte Carlo) rely on single particle wave functions whereas the few proton removal cross sections depend on clustering effects and the direct knockout of such clusters. The QMSFRG code [13] accounts for clustering but lacks a complete database of nuclear cluster models to perform the evaluation except in the case of a few light nuclei. Second, the mesons are in part responsible for the discrepancy in the low lineal energy GCR spectrum and needs added to the nuclear database and transport procedures and efforts on developing such a database has started. Third, there are several thousand energy and angle dependent cross sections for each material constituent required in shielding analysis. Very few of these cross sections have been validated in laboratory experiments and a systematic measurements program is required. The requirements for such a measurements program is discussed elsewhere [8]. Finally, although the HZETRN codes are more than a 1,000 times faster than the corresponding Monte Carlo codes even greater speed by using massively parallel processors along the usual 512 angular rays will greatly enhance the computational efficiency. Such speed is critical to the early entry of radiation constraints in the design process and optimization procedures.

Multifunctional materials optimization. Radiation shield optimization requires an evaluation of the design materials and making appropriate design choices at each step of the design process. Many choices will be driven by design requirements other than shielding and will usually be among less than perfect shield materials. The shield performance of candidate materials for each specific application need characterized to allow optimum choices to be made in the design process. New materials for specific applications need developed with enhanced shielding characteristics. Many such choices have already been identified for future designs. For example, polymer composites are preferable to aluminum alloys. Food and water are known effective shield materials and have been utilized in past design considerations. Hydrogen or methane fuels are potentially important materials for protection. We have proposed developing sound absorbing materials which are efficient radiation shields for use in crew areas. Recent advances in hydrogen storagein graphite nanofibers may have a large impact (3-6 times better than aluminum) on radiation safety in future spacecraft design.

Optimum protective materials. The requirements for a high performance shield material is to maximize the number of electrons per unit mass, maximize the nuclear reaction cross section per unit mass, and minimize the production of secondary particles. Thus, the transmitted LET spectra of hydrogen shows almost universal attenuation above a few keV/μ resulting in good attenuation of biological effects independent of biological model used. On the other hand, materials with less hydrogen content such as water experience attenuation only above 20 keV/μ. The LET attenuated components of higher Z materials continues to increase to higher values reaching 50 keV/μ for lead [1]. The maximum performance is for liquid hydrogen which we use to define the maximum performance limit of any material as shown in Fig. 3. It is a challenge to materials research to develop materials approaching these performance levels.

Concluding remarks.

At the beginning of this project, the shield design technology was at Technology Readiness Level (TRL) 3-4. The laboratory testing with relevant particle types has provided valuable data for model improvements and database validation. Future improvements will be more evolutionary than revolutionary as interaction models are relatively mature, which was not the case a few years ago and as confirmed by the blind test conducted by the LBNL group [16]. Future improvements are expected to be incremental. An opportunity for comparison with flight measurements on a large 2219 aluminum alloy structure allowed us to rapidly move the TRL to include level 6-7 elements in the project. The use of the tissue equivalent proportional counter (TEPC) with its broad spectral capability and the time resolved methodologies allows testing of codes and databases for both trapped proton spectra and galactic cosmic rays. This comparison added to the evidence that the pions may be the next most important component to add to the current technology, and consequently a low energy database for pion production has been prepared. The addition of higher energy multi-pion processes is in progress and will be funded out of another program. Only modest improvements to the exposure field are expected for spacecraft but the enhanced model may play a more important role for the Mars surface. Additional testing of the codes and database will take place on ISS in the near future. As a final note, the identification of polyethylene as a relatively efficient shield material under this project has resulted in an on-going activity with JSC for the augmentation of the ISS design to reduce the cancer risks of the astronauts in ISS operations.

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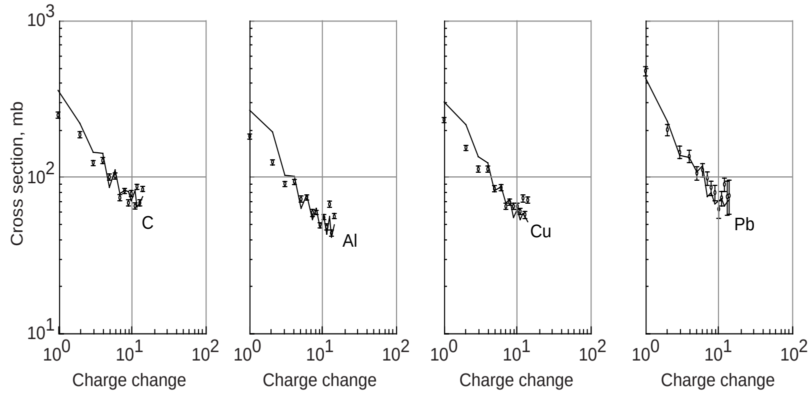

Figure 1. Charge-changing cross sections for ΔZ from -1 to -14 for 1.05 GeV/nucleon ^{56}Fe incident on C, Al, Cu, and Pb targets. The solid lines are predictions from QMSFRG

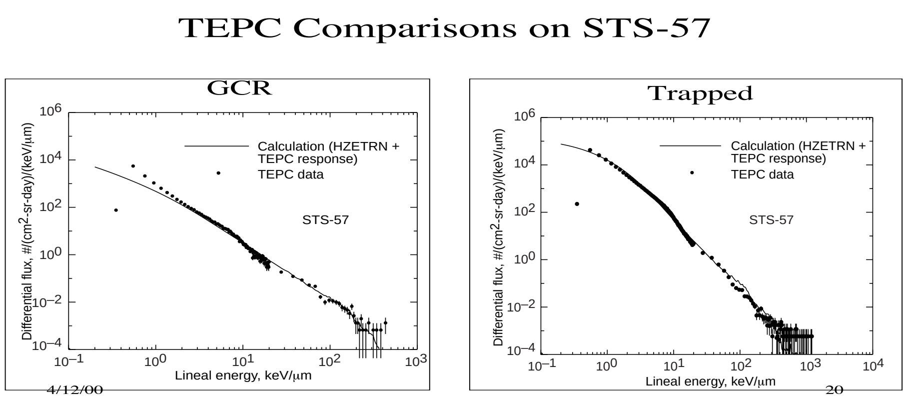

Fig. 2. TEPC measurements on STS-57 compared to model calculations.

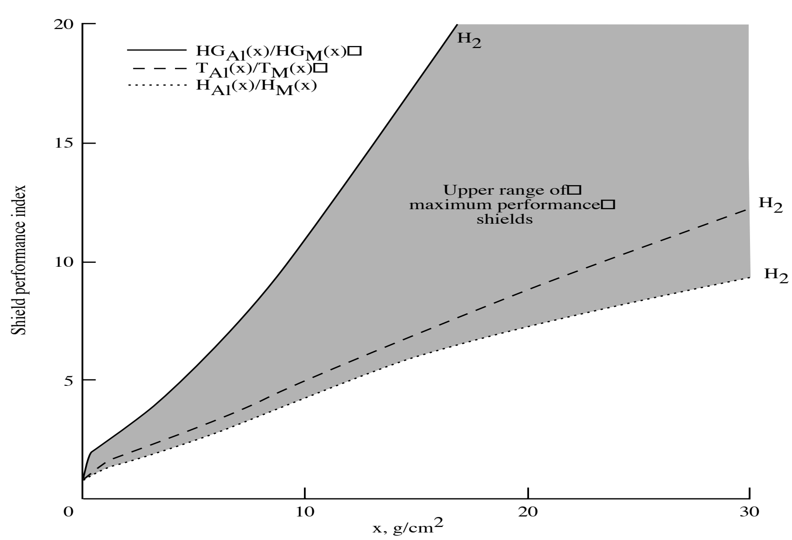

Fig. 3. Maximum performance factors for any material relative to aluminum.